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USE OF THE MAXIMUM ENTROPY METHOD TO RETRIEVE THE VERTICAL ATMOSPHERIC OZONE PROFILE AND PREDICT ATMOSPHERIC OZONE CONTENT

A report submitted to the Graduate Intern Program
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by

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Graphs and results are proprietary material

Subscribed and sworn to before me in my presence, this 31 day of July, 1991, a Notary Public in and for the State of Maryland.

Notary Public

My Commission Expires August 1, 1993

INTRODUCTION

* In 1934, Gotz and Dobson made a fundamental study on the problems associated with inversion of radiance measurements for atmospheric ozone profiles.

* First method for vertical atmospheric ozone distribution from satellite measurements presented by Singer and Wentworth.

* The current National Space Science Data Center algorithm for BUV (Nimbus-4) and SBUV (Nimbus-7) archives is based primarily on the work of C.D. Rodgers.

* This method formulated in terms error covariance matrices, is associated with both direct measurements, apriori first guess profiles, and a weighting function matrix.

STATEMENT OF THE PROBLEM

Profile Retrieval

Power Spectrum

1. Profile retrieval: Achieved by Inversion of Radiative Transfer Equations.

$$\int K(x)\, x\, dx = y \quad \text{(Fredholm Integral/1st kind)}$$

K = Kernel (Planck Radiation Law/Maxwell Equations)
x = unknown profile
y = given data set of radiance values

* To numerically solve: K(x) assumed independent of x. Then the equation is written in a linearized form:

$$y = Ax + \eta$$

A = weighting function matrix
η = noise

* Standard Approach
  -- Ignore η
  -- Find A^{-1}
  -- Solve $x = A^{-1}y$

* Problems:
  1. The A matrix is near singular

  2. Number of Unknowns in the profile exceeds the number of data points (The Ill-Posed Problem) Therefore, the solution may not be unique.

  3. Even if a unique solution exists, η may cause the solution to be ill-conditioned.

MAXIMUM ENTROPY SOLUTION

* Since the number of unknowns exceeds the number of data points. probability theory is needed.

* Introduce Maximum Entropy formalism which induces an unknown probability distribution from partial data.

* Maximize the information measure subject to the following constraints:

  -- Sum of the probabilities is 1.

  -- The data, given as averages, is written in the form of expectation values.

* Solution: An exponential probability distribution,

$$p_i = \exp[- \sum_i \lambda_i A_{i,i}] \;/\; Z(\lambda_i)$$

where λ_i = Lagrange multipliers, and
$Z(\lambda_i)$ = Partition function.

2. Power spectral estimation for a time series of TOMS data.

In 1967 Burg introduced his Maximum Entropy Method (MEM) for power spectral estimation

$$P(f) = \frac{(P_N + 1)/f_N}{2\left|1 + \sum_{n=1}^{N} a_{Nn} \exp[-2\pi\, if\, n\Delta t]\right|^2}$$

- P_N is the prediction filter error power
- a_{Nn} are the filter coefficients
- f_N is the Nyquist/sampling frequency

The coefficients are obtained from the Yule-Walker equations:

$$\begin{pmatrix} \phi_0 & \phi_1 & \cdots & \phi_N \\ \phi_1 & \phi_0 & \cdots & \phi_{N-1} \\ \vdots & \vdots & \ddots & \vdots \\ \phi_N & \phi_{N-1} & \cdots & \phi_0 \end{pmatrix} \begin{pmatrix} 1 \\ a_{NA} \\ \vdots \\ a_{NN} \end{pmatrix} = \begin{pmatrix} P_{N+1} \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

- ϕ_N are the time-corelations functions of the data.
- Length of the filter, N, has to be determined.

RESULTS

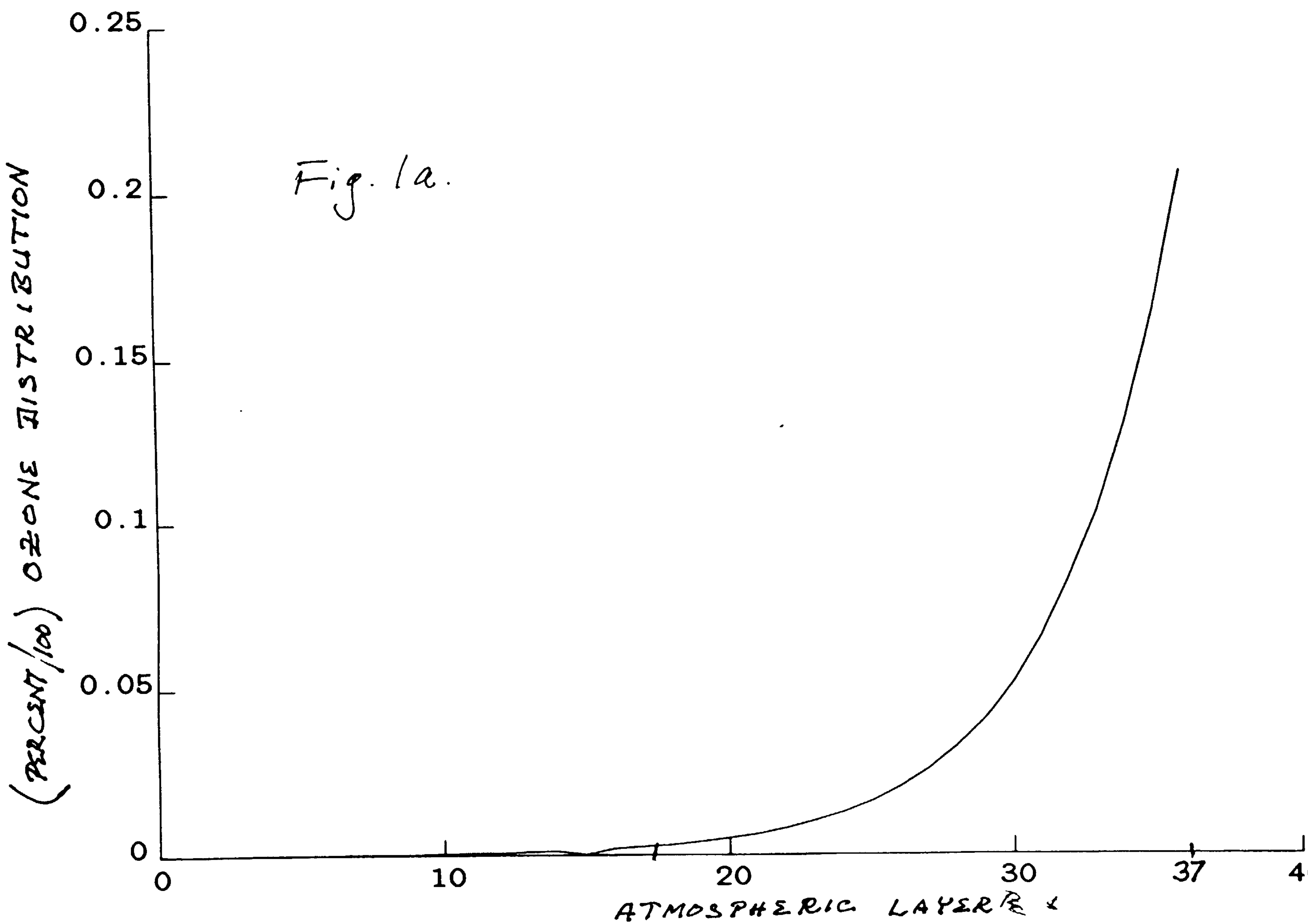
The cases depicted in the Figures are preliminary and being refined for publication in two separate journals of the joint American and European physical societies. Figures 1a and 1b show the case of the ozone profile retrieval as done by then National Space Science Data Center and the Maximum Entropy Method respectively. The latter shows a clear depletion of ozone for data taken by Nimbus-7 in the antarctic region. Likewise, in figures 2a and 2b, for a mid-lattitude sampling, the Maximum Entropy shows a more realistic ozone depletion picture.

Figures 3a, 3b and 3c involve the time-series and Maximum Entropy power spectra for the city of Hyderabad, India for the active solar year 1979. The randomness and periodicities evident in the TOMS time series is clearly confirmed in Figure 3b. More important, the three expected abnormalities, namely the 28 day solar cycle, the mid-year peak due to the change of equinoxes and the annual cycle of the motion of the ecliptic are present. This is strong evidence for the validity of this approach. The other cycles are being studied with perhaps a correlation of the 210 day cycle with the half period of the Chandler wobble as a possibility. The 80 day sample was performed as a check of both the stationarity of the series and the authenticity of the 365 spectrum cycles (Fig 3c). This confirms the origin of the physical processes governing the spectral periodicities as arising very early within the solar year!

Figures 4a and 4b are the TOMS time series and full Maximum Entropy spectrum for Hyderabad for the less active 1980 year. A slight shift in both the dynamic range and frequency again clearly show that the series are not quite stationary from year to year, but the major cycles remain. In all cases, a comparative FFT Spectrum could resolve no more than the mid-year peak and was therefore abandoned.

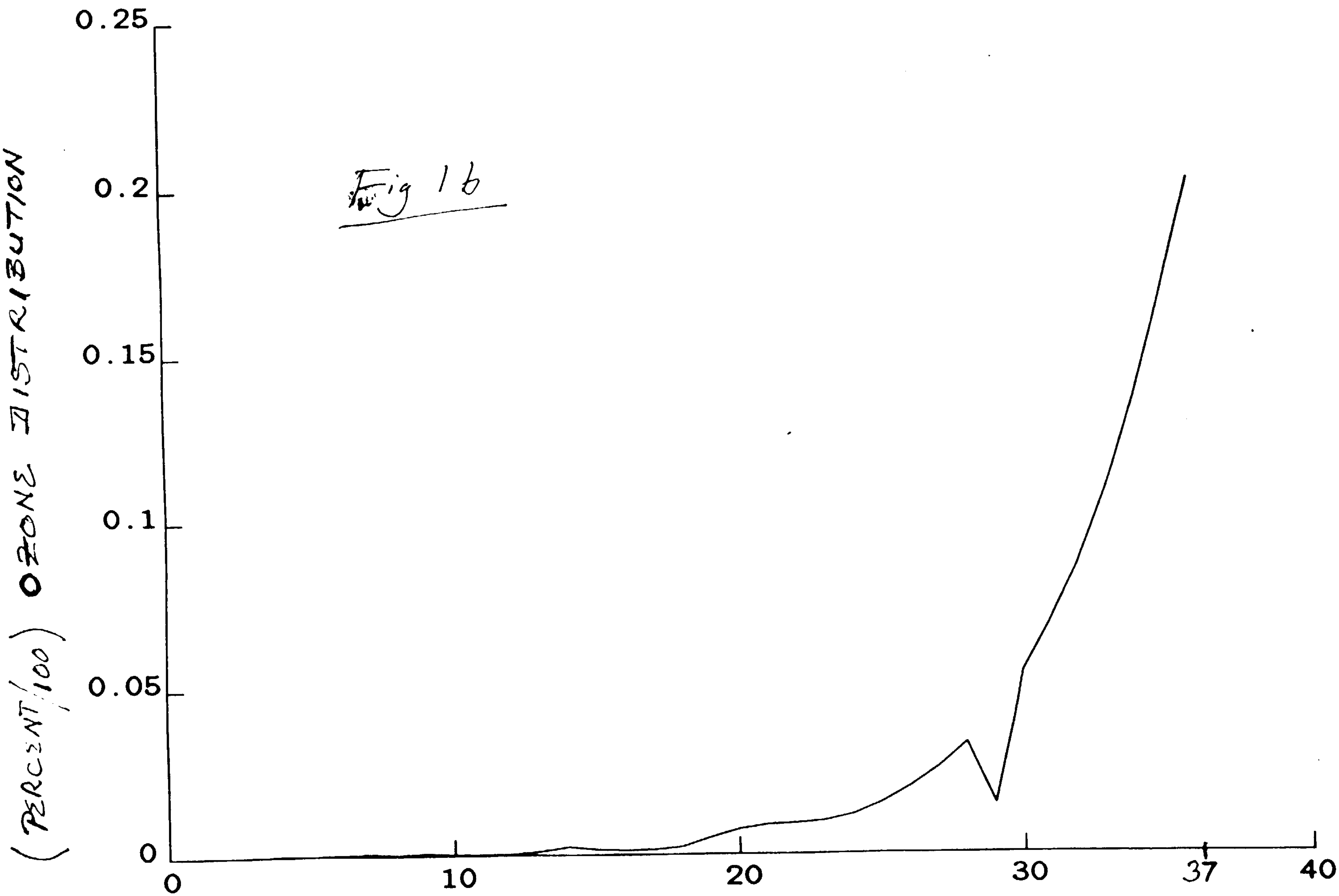
The remaining cases show both the time series and resulting full and partial sample spectra New York City (41° lat) and SYOWA (Japanese) antarctic station (-70° lat). The New York data shows a much larger random spread than Hyderabad and this resulted in a larger number of multiple frequencies in the spectrum. A greater number of major cycles are present as are some of those found in Hyderabad data including the speculative half period Chandler wobble.

The SYOWA spectrum was calculated for the cases of 134 days (up to the Sun gap), and 365 days (including the gap) and again, a short sample of 80 days. This was done in part to study effects such as the quasi-bilinear-oscillation (QBO). More work needs to be done at this point to estimate correctly the secular trends in total ozone.



VERTICAL ATMOSPHERIC OZONE DISTRIBUTION BY NSSDC ARCHIVES ALGORITHM
(NIMBUS-7 POLAR CASE)

Fig 1b



VERTICAL ATMOSPHERIC OZONE DISTRIBUTION BY MAXIMUM ENTROPY INVERSE

(NIMBUS-7 POLAR CASE)

SET4UNK.DIS DATA: N = 20 08-06-.90 09:00:27

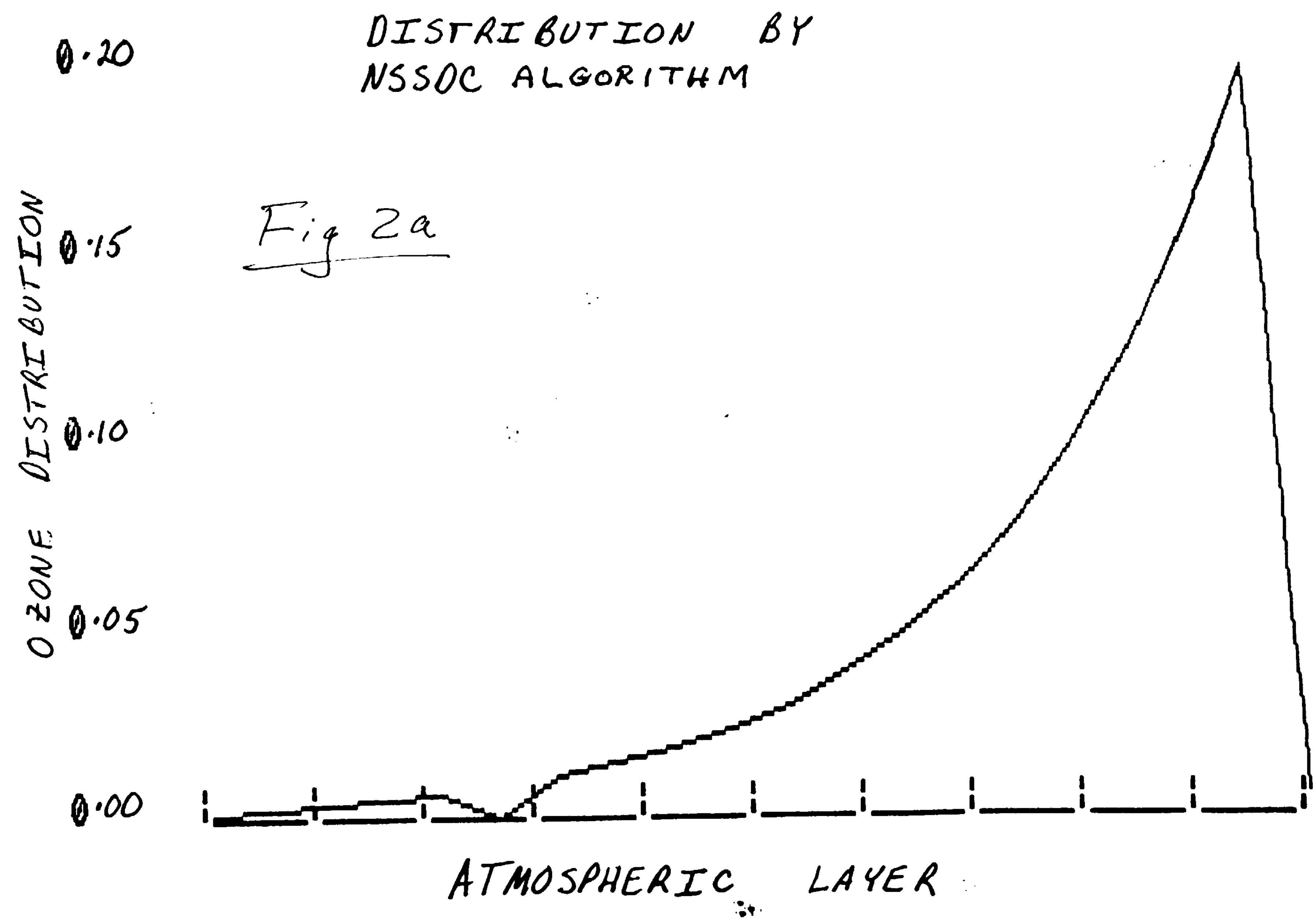


Fig 2a

set4con.dis DATA: N = 19 08-[illegible]-1990 08:54:12

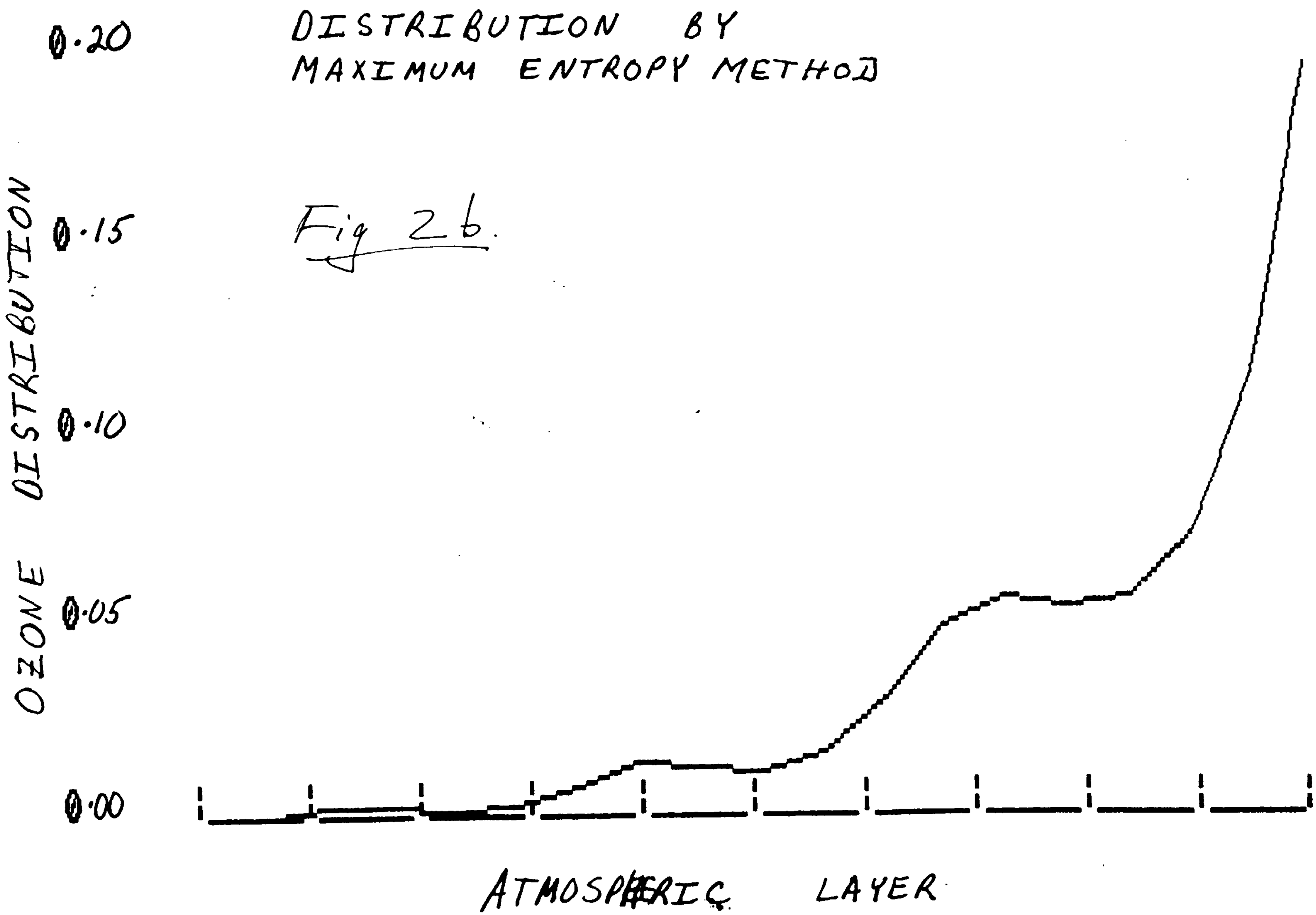
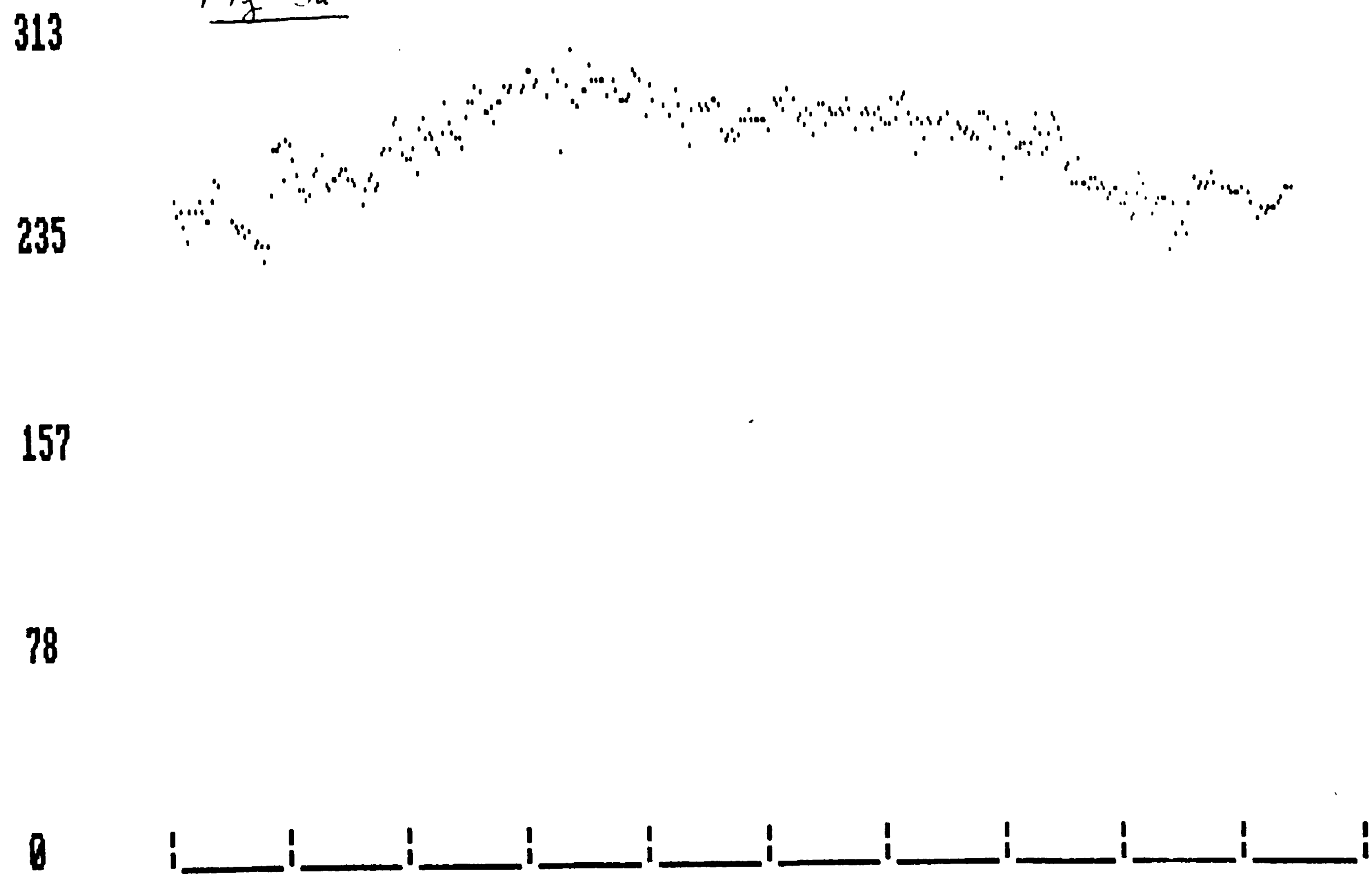


Fig 2b.

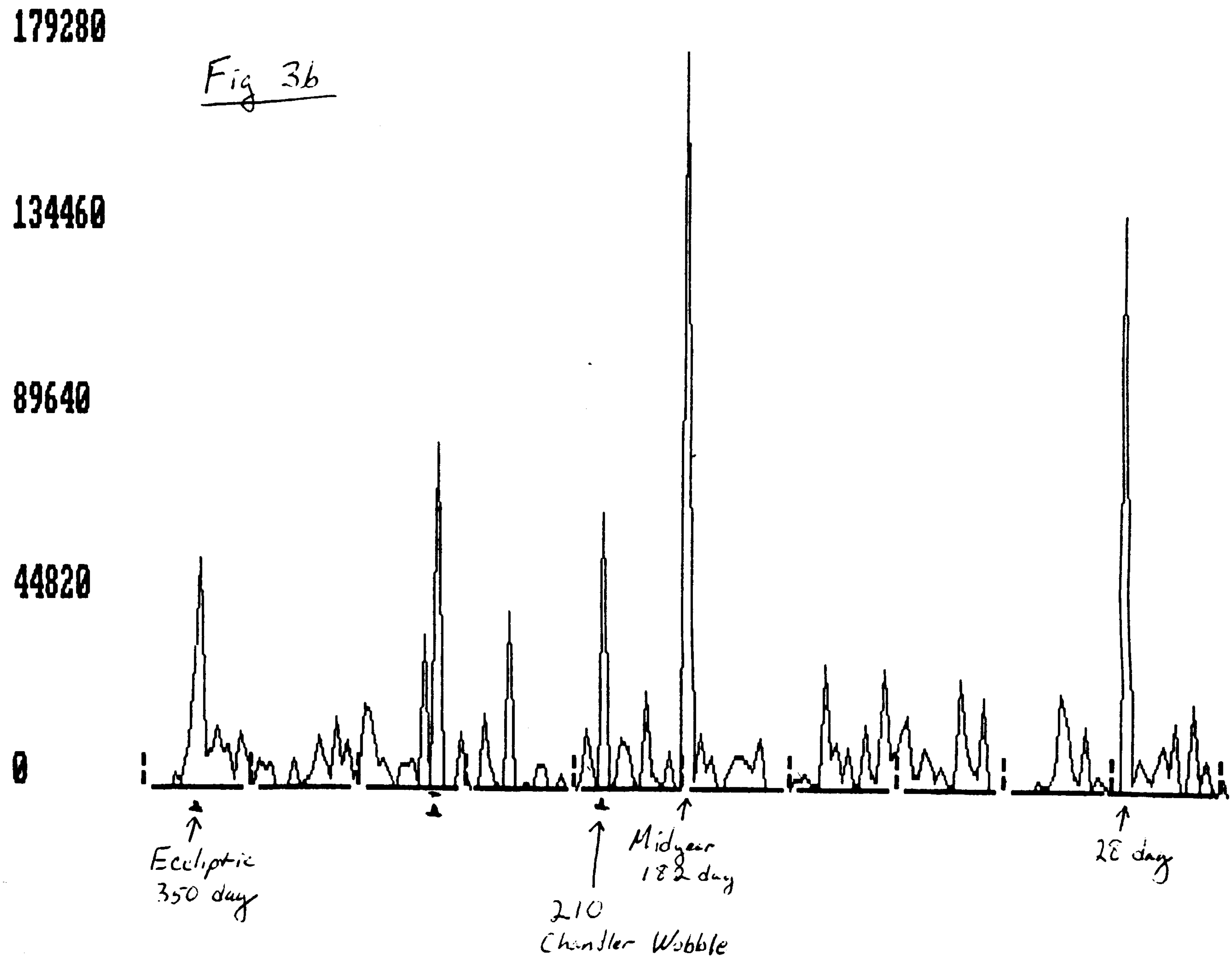
TOZ.DAT DATA: N = 366 01-01-198_ 05:47:51

Fig 3a



TOMS Hyderabad, India - 1979

Fig 3b

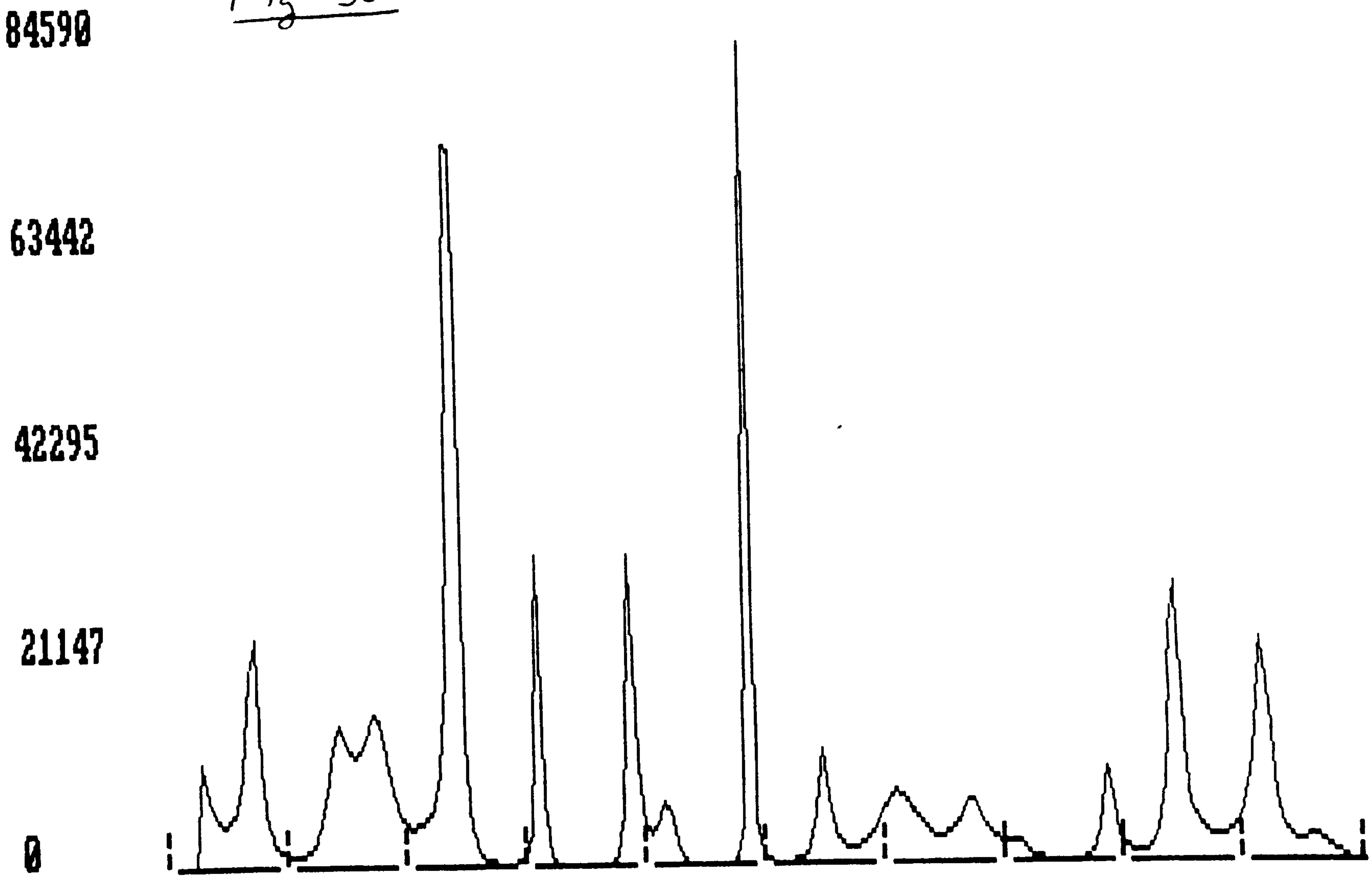


Max Ent Spectrum for Fig 3a

79?_?8040.dat DATA: N_{out} = 182 01-01-198? 03:49:00

(N = 80 days)

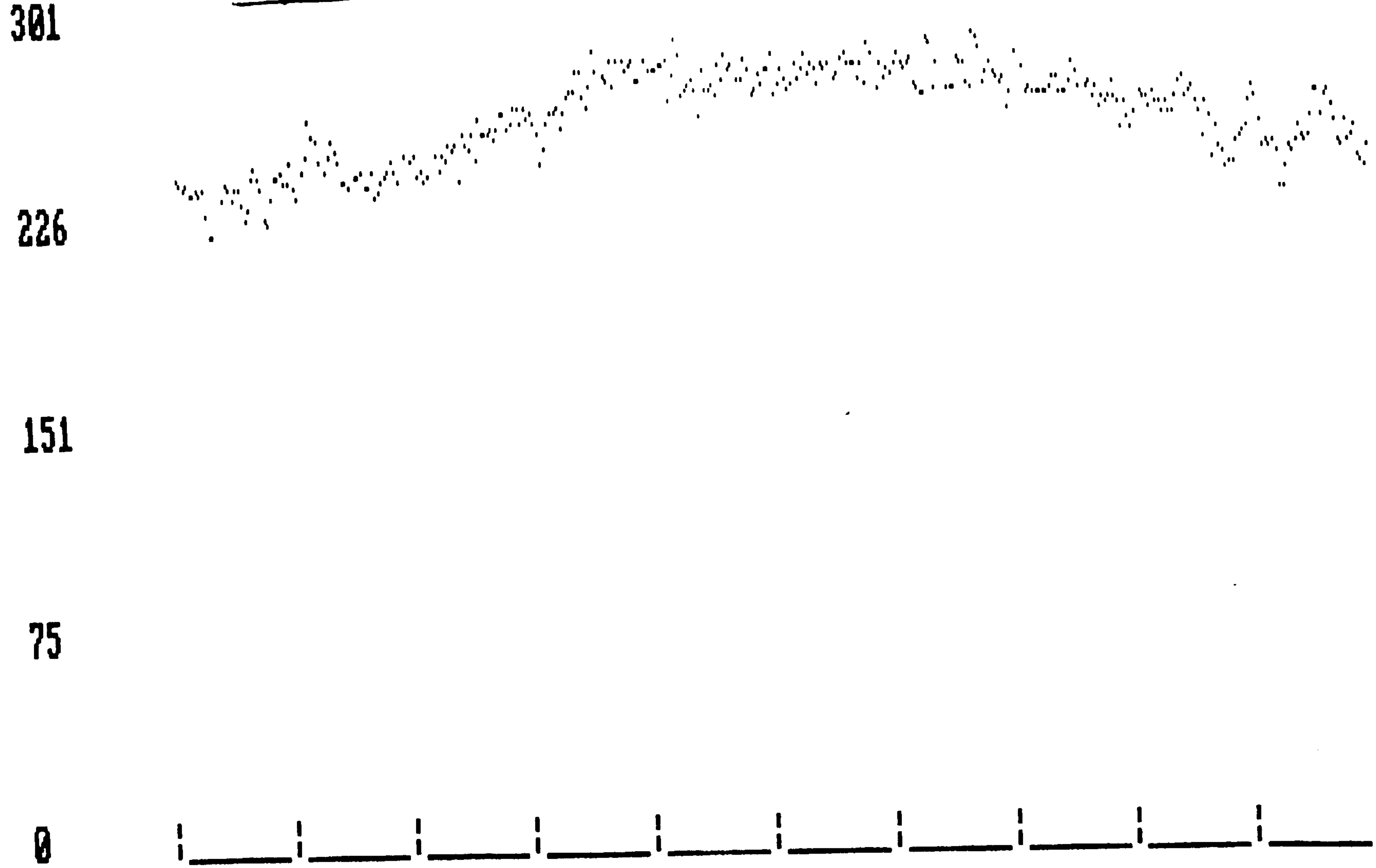
Fig 3c



80 day Max Ent Spectrum for Fig 3a

TO2680.DAT DATA: N = 366 01-01-1980 0?:15:08

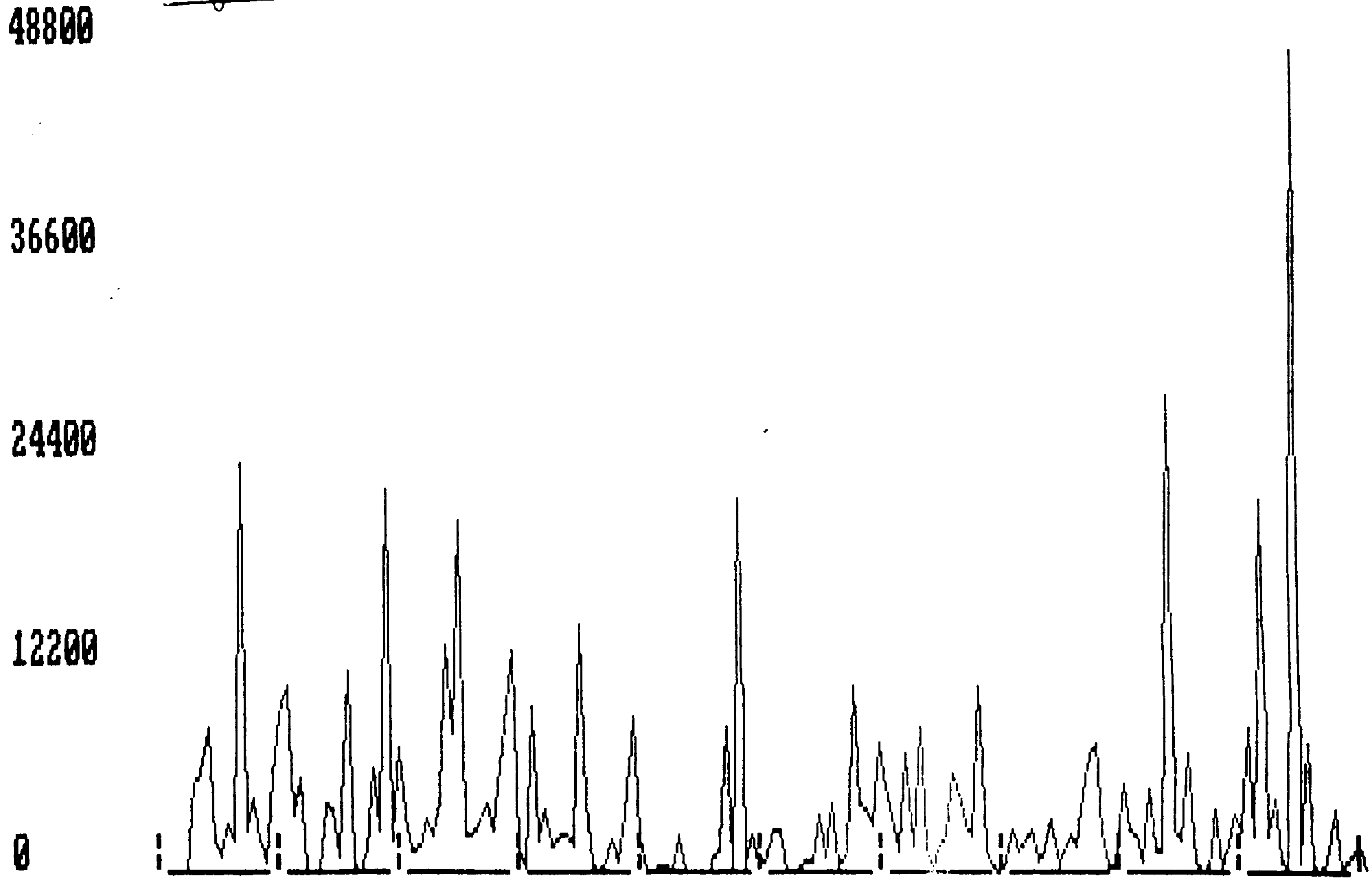
Fig 4a



TOMS for Hyderabad, India - 1980

80spc170.dat DATA: N = 182 01-01 .980 05:09:07

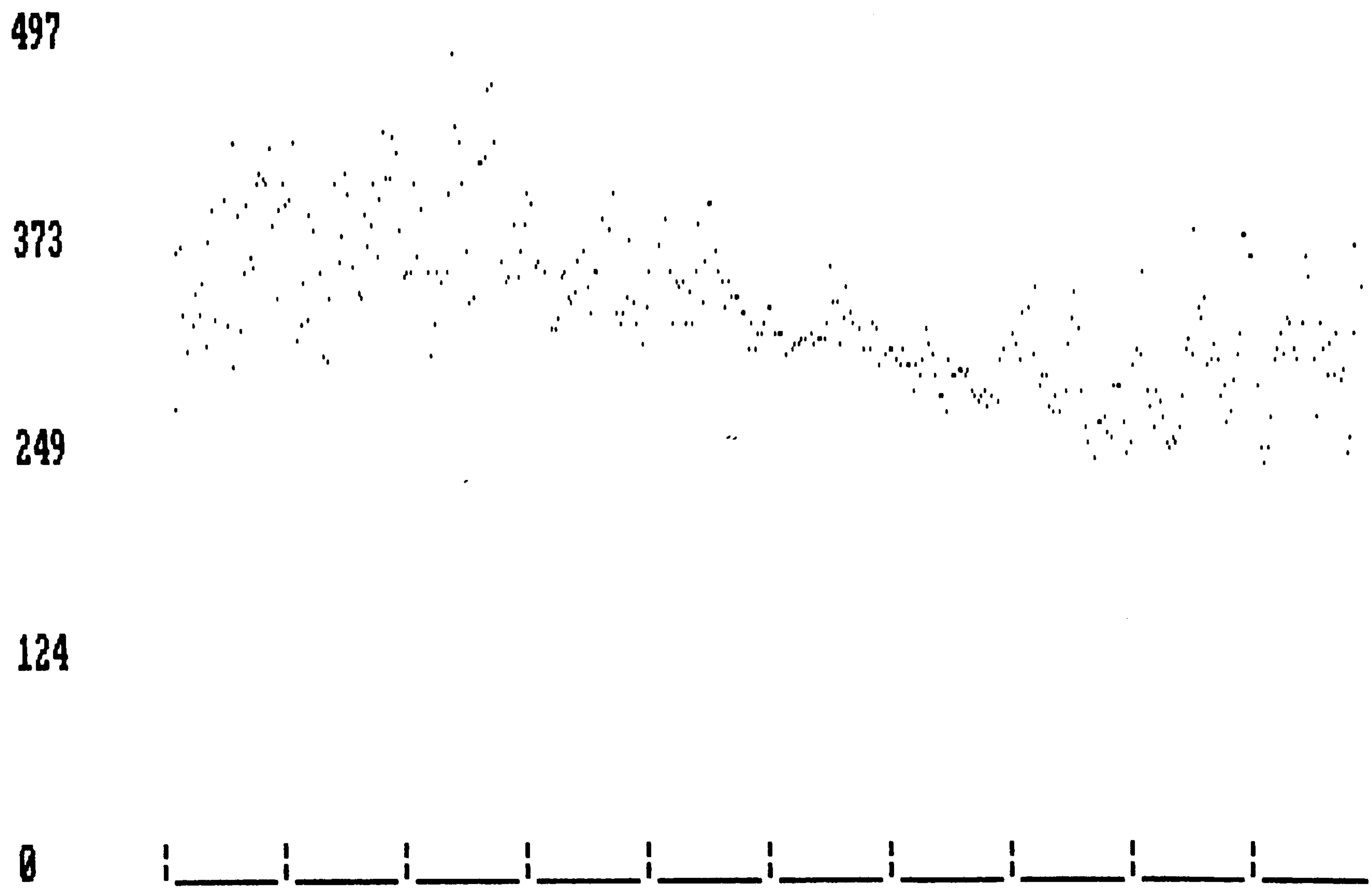
Fig 4b



Max Ent Spectrum for Fig 4a

SNEWYORK.DAT DATA: N = 371 01[illegible]-1980 04:42:16

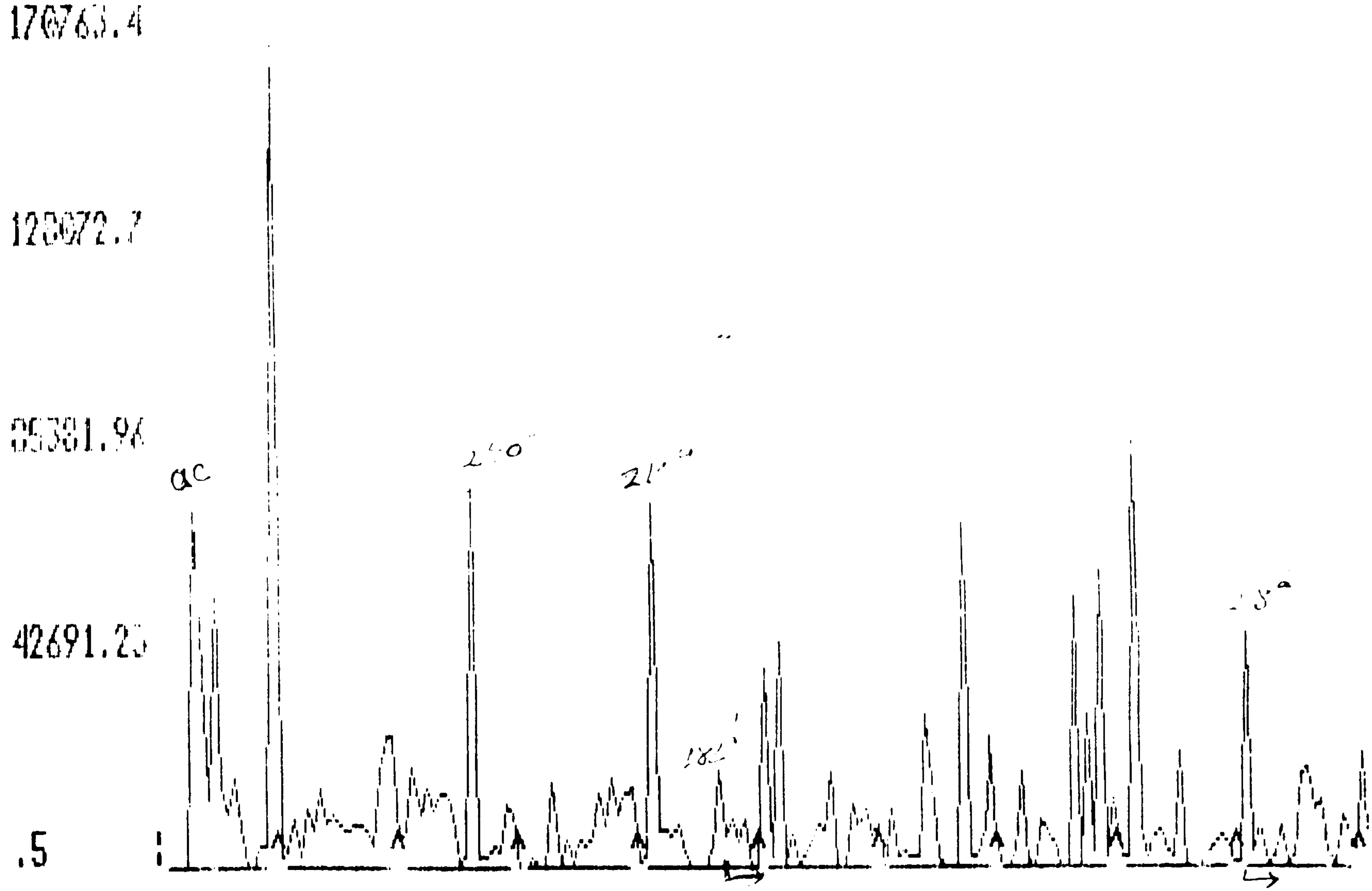
Fig 5a



TOMS - New York City - 1979

New York City 1979 K = 178

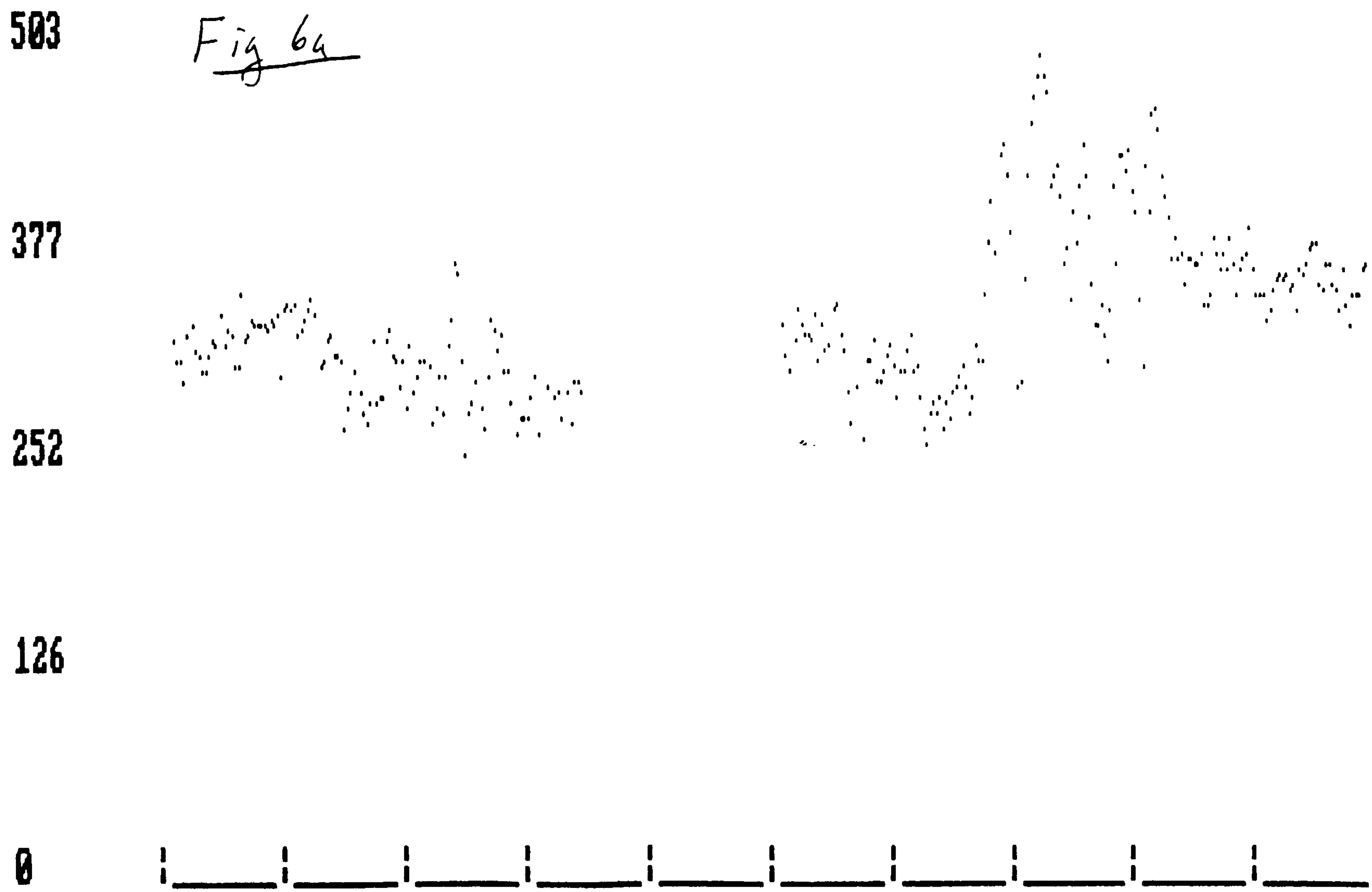
Fig 5b



Max Ent Spectrum for Fig 5a

_syowa.dat DATA: N = 371 01-01-198 00:44:37

Fig 6a

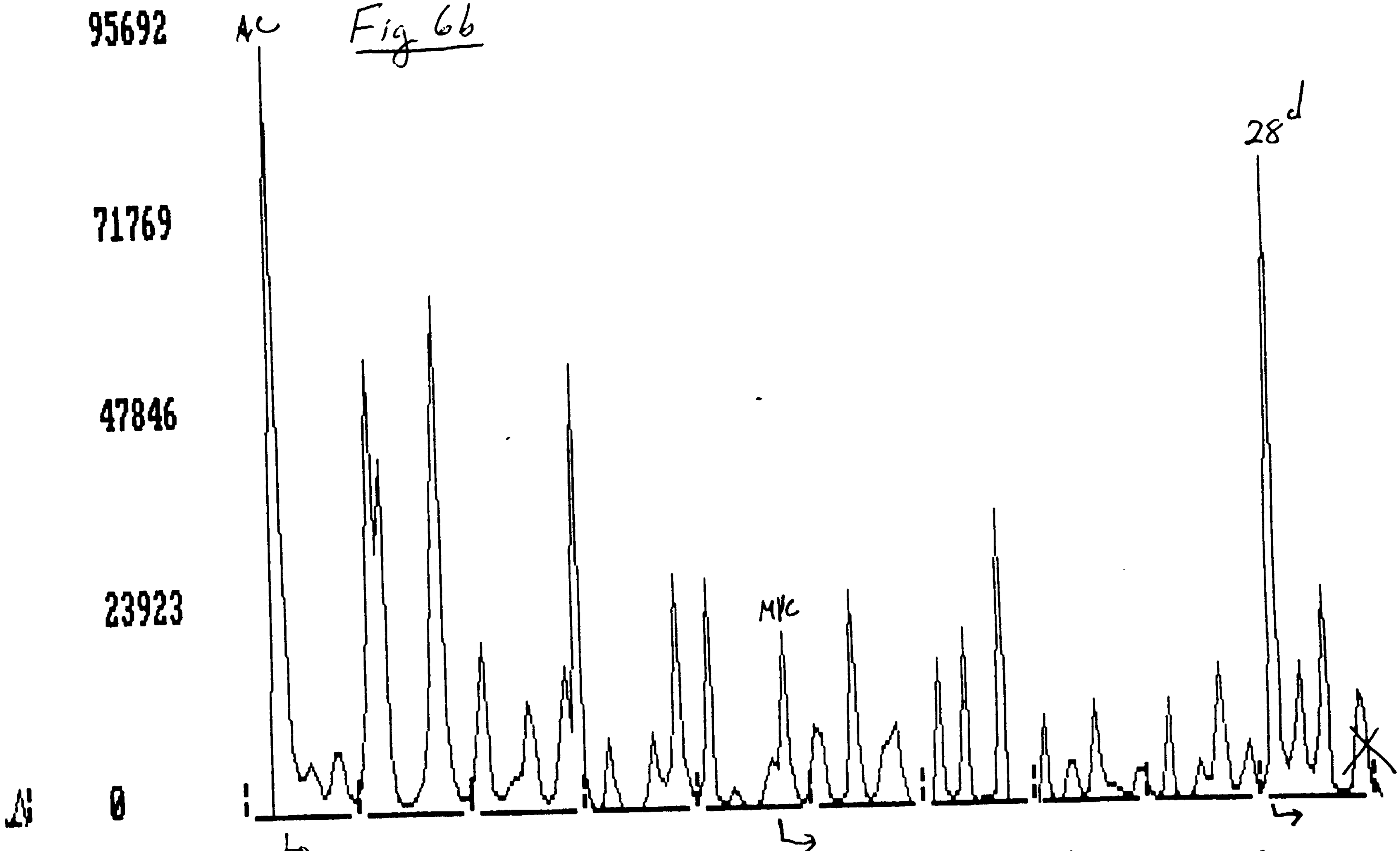


TOMS - Syowa - 1979 - Japanese Antarctic Station

79syp90.dat DATA: N = 182 01-6..1980 00:21:14

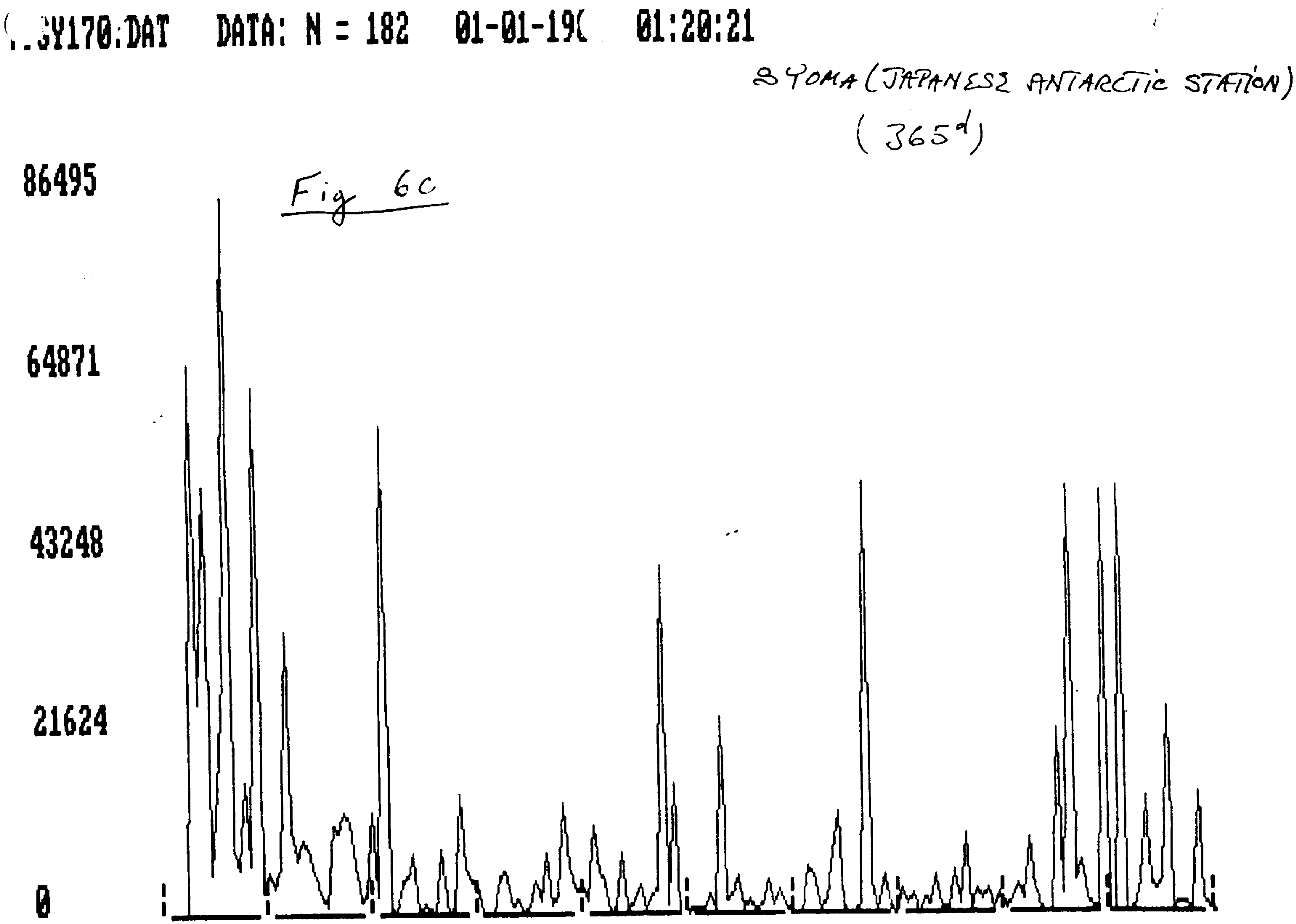
134 d

Fig 6b



Max Ent Spectrum for 134 day Sample from Fig 6a

Fig 6c



Max Ent Spectrum for a full 365 day sample from Fig 6a